Requirements for Development of Thermal Protection Materials for Multiple Planetary Missions

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Session VI: Entry, Descent, and Landing Technologies for Planetary Missions

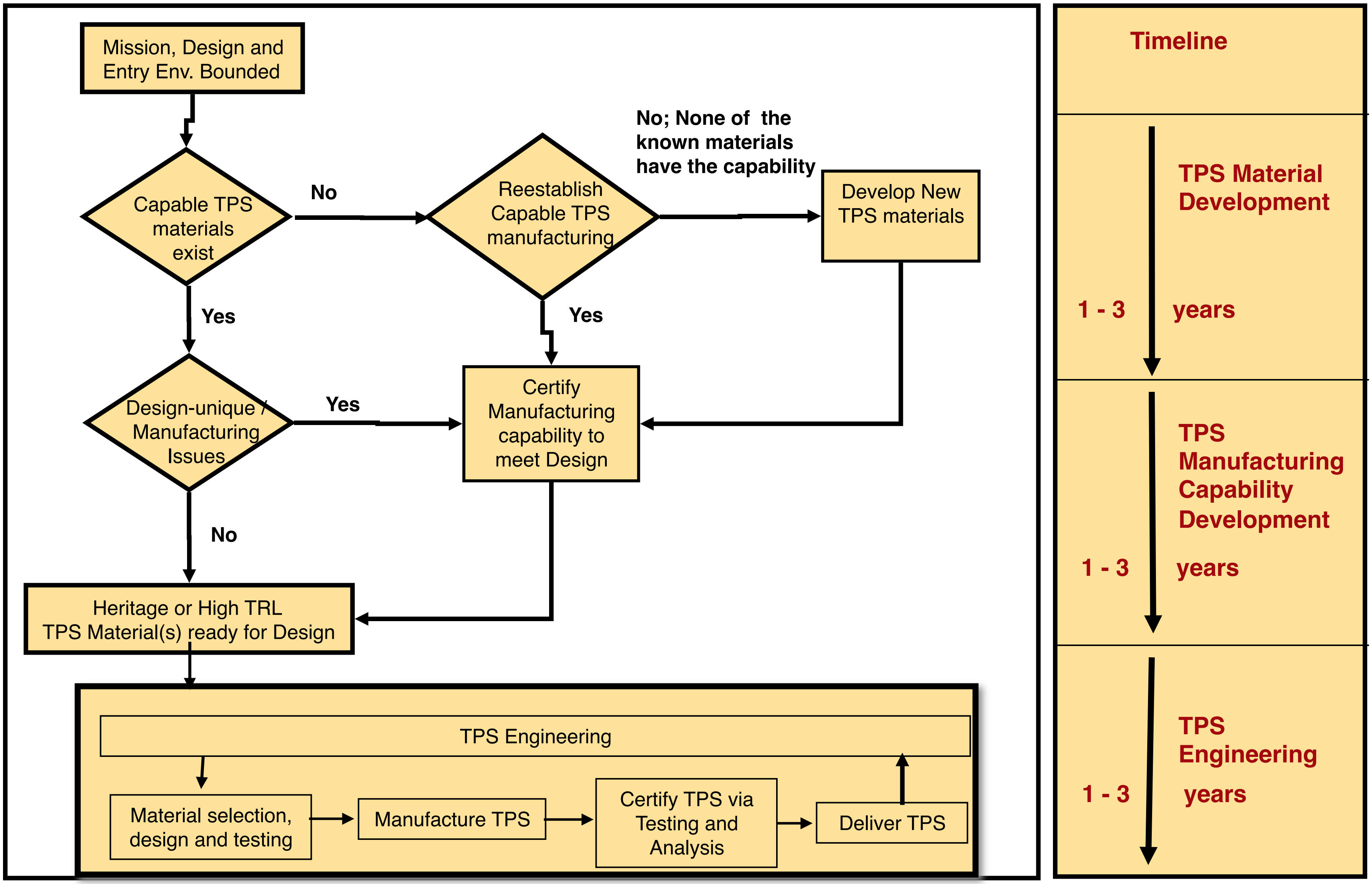
Historical Perspective: Ablative TPS

- **TPS Investment in the 60's - Focused Program - Technology development with specific mission goal**
  - Material Performance, Heat Shield System Development and Design Architecture
  - Test, Test and more Test
  - Ground and flight test => Material behavior, Analytical capabilities and model development
- **Apollo 1960's - 1970' Avcoat 5026-39/HC-G**
  - Developed H/C System due to reliability risk of tiled approach
    - Needed a lighter weight system compared to DOD TPS (Carbon- or Quartz Phenolic)
  - Too heavy for Mars entry - Viking
- **Viking (1975) SLA-561**
  - Used low density silicone in H/C - similar to Apollo TPS
    - Good insulator with a robust architecture
- **Pioneer-Venus, Galileo**
  - NASA didn't have materials to handle entry conditions
  - DOD investment in carbon phenolic leveraged to these missions
  - But, NASA did not fully explore material performance limits due to facility capability (e.g., spallation on Galileo)

TPS Technology Investment: Post Apollo/ Viking Era

- **Reusable materials technology investment in the late 70's through 80's/mid 90's (Reusable Systems - Shuttle)**
  - Very limited investment / efforts in Ablative TPS
    - Reusable Systems for Low Earth Orbit (LEO)
  - Faster, Better and Cheaper philosophy - Genesis and Stardust
- **Project Choice**
  - Pathfinder used Viking as heritage
  - MER used Pathfinder as heritage
  - MSL is using all of this as heritage
- **Mission Proposals are handicapped by lack of investment in and characterization of TPS**
  - Jupiter Multi-Probe
  - Mars Sample Return
  - Venus Probe Mission
  - Comet and Asteroid Sample Return Missions

Timeline: TPS Development to Engineering Solutions to Missions



Heritage Argument

- **The heritage argument is seriously flawed since "heritage" involves more than material performance when applied to a system**
  - Traceability from ground test to flight
    - via math models
  - Integration
  - Scale
    - (Test to flight) article size limited by test facilities
  - Manufacturability
  - Verification & validation:
    - From component to full scale system
    - Thermal, Thermo-structural, Thermal cycling/ thermal vac, vibro-acoustic, MMOD
- **Some challenges can be handled by engineering and others cannot be**
  - Stardust accepted the risk in PICA
  - PICA was originally baselined for Genesis
    - Manufacturing and design integration issues led to changing from PICA to C-C
  - Can PICA be designed with gaps & seams for Lunar Return?

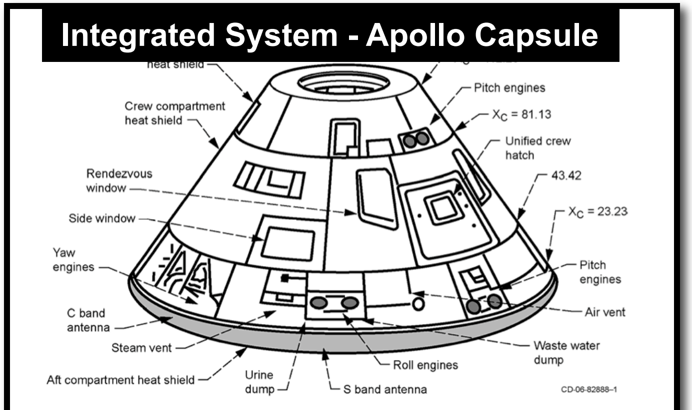
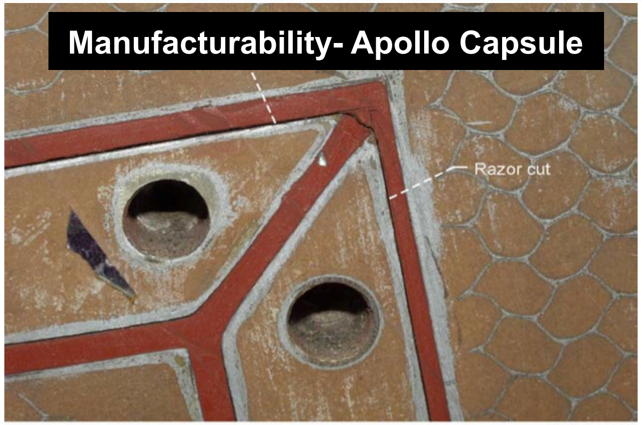


Figure 1. Apollo Block II command module.[5]



SLA Story: Easier Missions are past …
Future Missions are more demanding ….

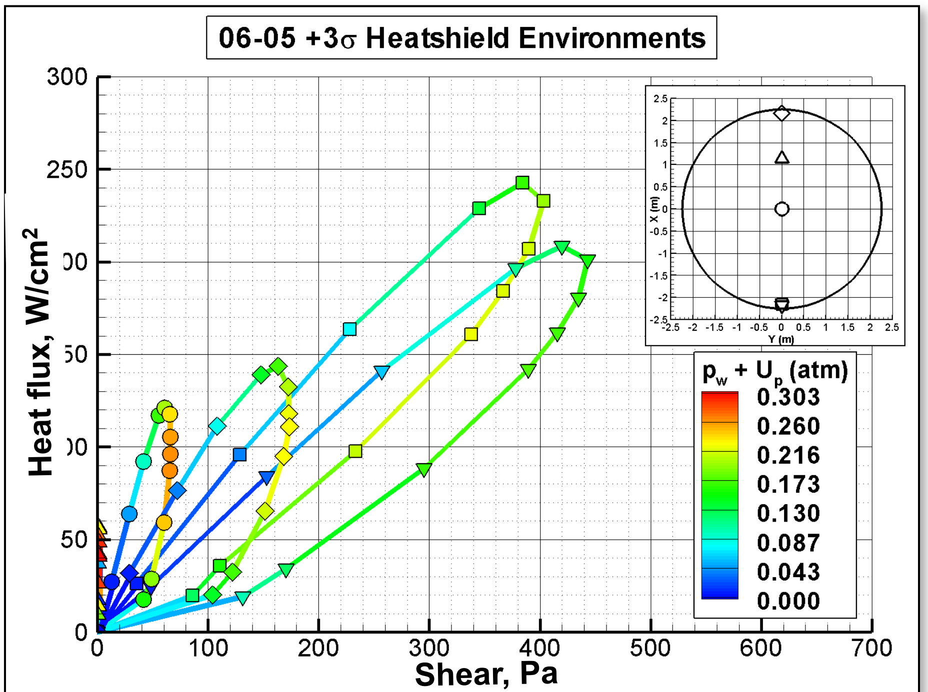
Heritage Issues (Materials and Missions)

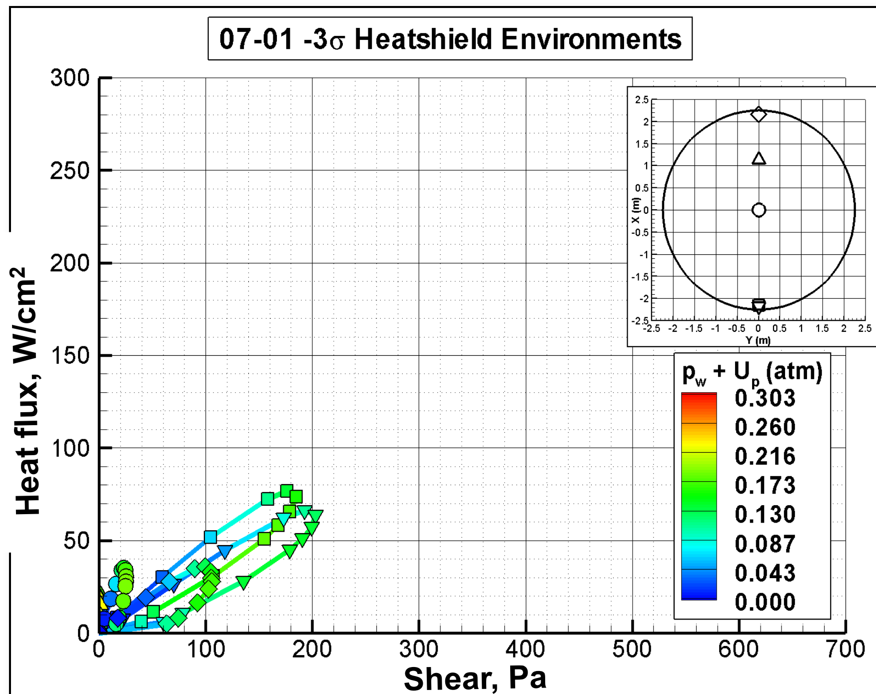
Parameter	Viking	Pathfinder	MER	MSL
Shape	70° blunt cone	70° blunt cone	70° blunt cone	70° blunt cone
Diameter (m)	3.54	2.65	2.65	4.50
Vehicle mass (kg)	980	585	836	3400
Relative entry velocity (km/s)	≈ 4.40	7.48	5.55	5.93
Trim angle-of-attack (deg)	-11.1	0	0	-15.8
Ballistic coefficient (kg/m^2)	63.0	62.3	88	140+
Peak heat flux (W/cm^2)	≈ 21	105.8	44	≈ 234
Total heat load (J/cm^2)	≈ 1100	3865	3867	≈ 6000
PH stagnation pressure (atm)	0.06	0.19	0.06	0.25
Forebody TPS	SLA-561V	SLA-561V	SLA-561V	SLA-561V
Backshell TPS	None	SLA-561S	SLA-561S	SLA-561V

Significantly larger than any prior Mars mission

SLA & MSL: The Recent Challenges

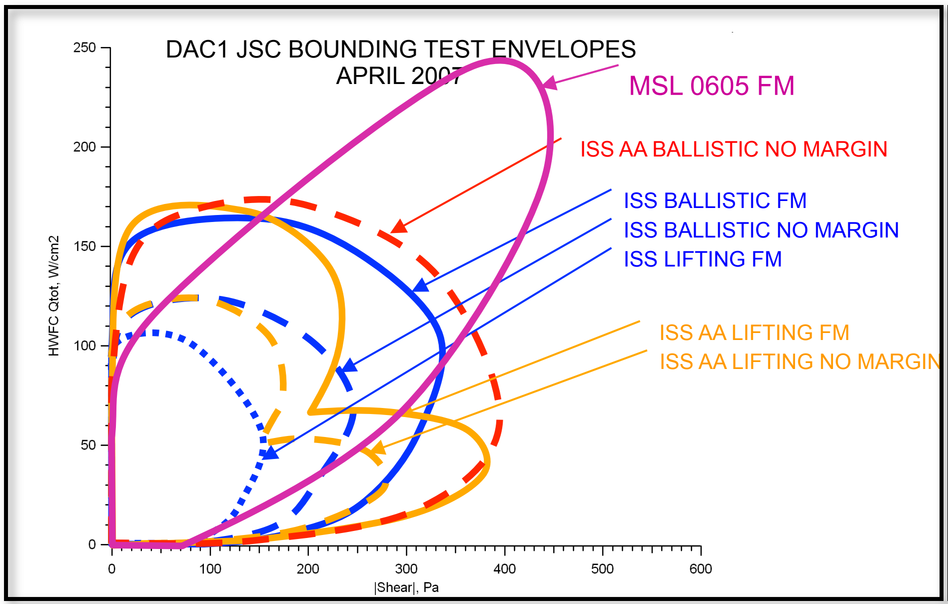
- **Requirements Driver and evolution**
  - Landing site selection to happen late in the project cycle
  - TPS requirement flow needed to be done with the flexibility to choose landing site
- **Evolving Trajectory Space Defines the Environment**
  - Challenge: Bounding requirements
    - needs to be evaluated so as to mature the design, manufacture and verify
- **Key Aerothermal environment**

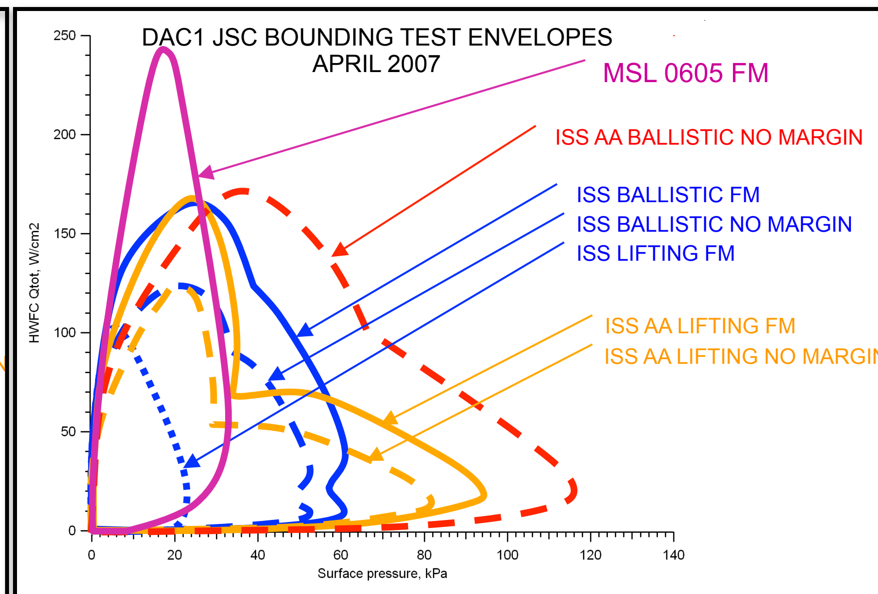




SLA: MSL vs. CEV Block I (ISS Return)

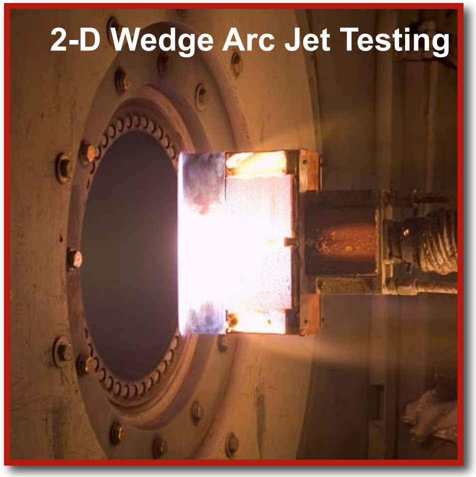
- **Evolving Requirements**
  - TPS material testing for Human Mission - Qualification and Certification are the key - test facility capability to verify design is essential
- **Trajectories Comparison between MSL and CEV ISS Return**
- **Key Aerothermal environment parameters that impact SLA selection and thickness**
- **Manufacturability (Heritage vs. what is required) for CEV Heatload**
  - MSL (~ 6 kJ/cm^2) vs. CEV ISS Return (~ 50 kJ/cm^2) heat load determines the TPS thickness if SLA can perform to the combined aerothermal environment





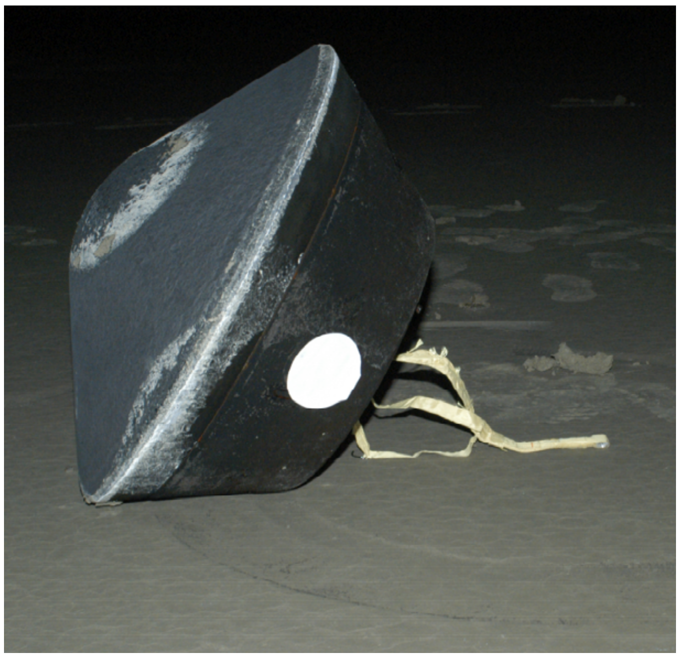
SLA Story: Understanding Limits

- **Why do we need to Understand SLA Capability Limit for MSL and CEV**
  - Uncertainty in performance or flexible requirements need vs. robust design
  - Robust design means staying away from cliffs (limit behavior) with plenty of Margin
- **Manufacturability (Heritage vs. what is required)**
  - Can you build a TPS as designed?
- **Prior missions at threshold of recession; MSL much higher heat flux, pressure, shear + turbulent flow**
  - Mars Technology Program funded extensive arc jet testing; discovered that ablation mechanism is related to glass vaporization, melt flow
  - New series of tests underway to understand melt flow dependency on shear
- **Why wasn't this done 20 years ago?**



PICA Story

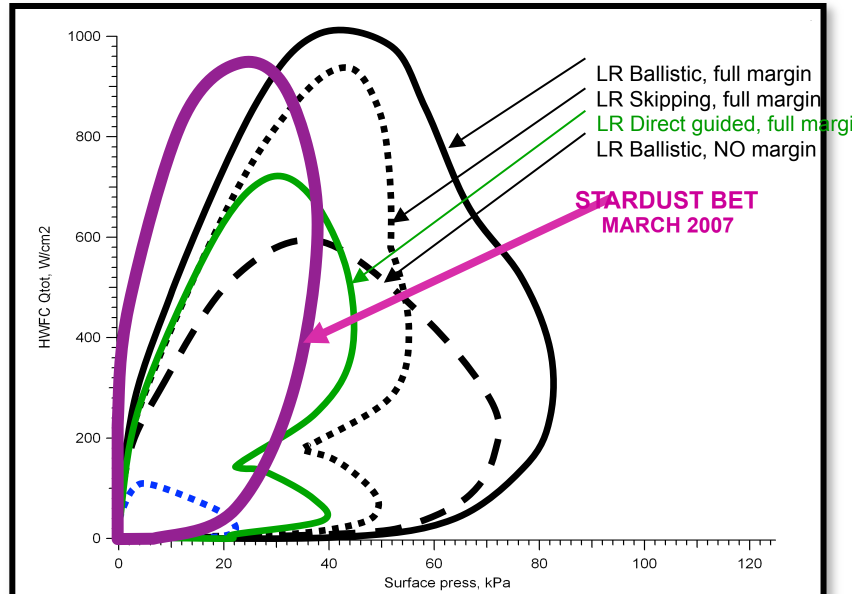
- **Low-density carbon based ablator used for Stardust forebody TPS; fabricated as 1-piece heat shield**
- **Primary TPS for Orion lunar return forebody heat shield**
  - Scale of Orion requires fabrication as blocks bonded to aeroshell
  - Introduces gaps between blocks that require robust gap filler (system issue)

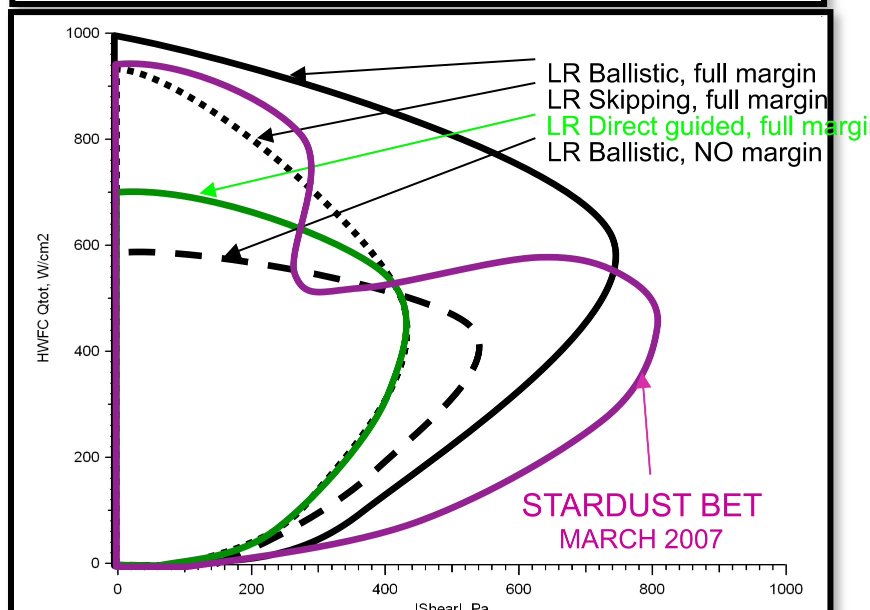


Comparison of Stardust and CEV Lunar Return

Parameter	Stardust	CEV Lunar Return
Diameter (m)	0.827	5.0
Max heat flux (W/cm^2)	950	800
Total heat load (kJ/cm^2)	36	100
Max pressure (kPa)	36	65
Max shear (Pa)	800	725
TPS thickness (cm)	5.82	~ 10.0
Forebody penetrations	None	6 comp pads
H/S Retention	Attached	Separating
Manufacturability	Monolithic 1-piece PICA	PICA tiles with gaps & seams
MMOD requirements	None	6 months MMOD exposure

The time to study and fully understand the limits of PICA is NOW

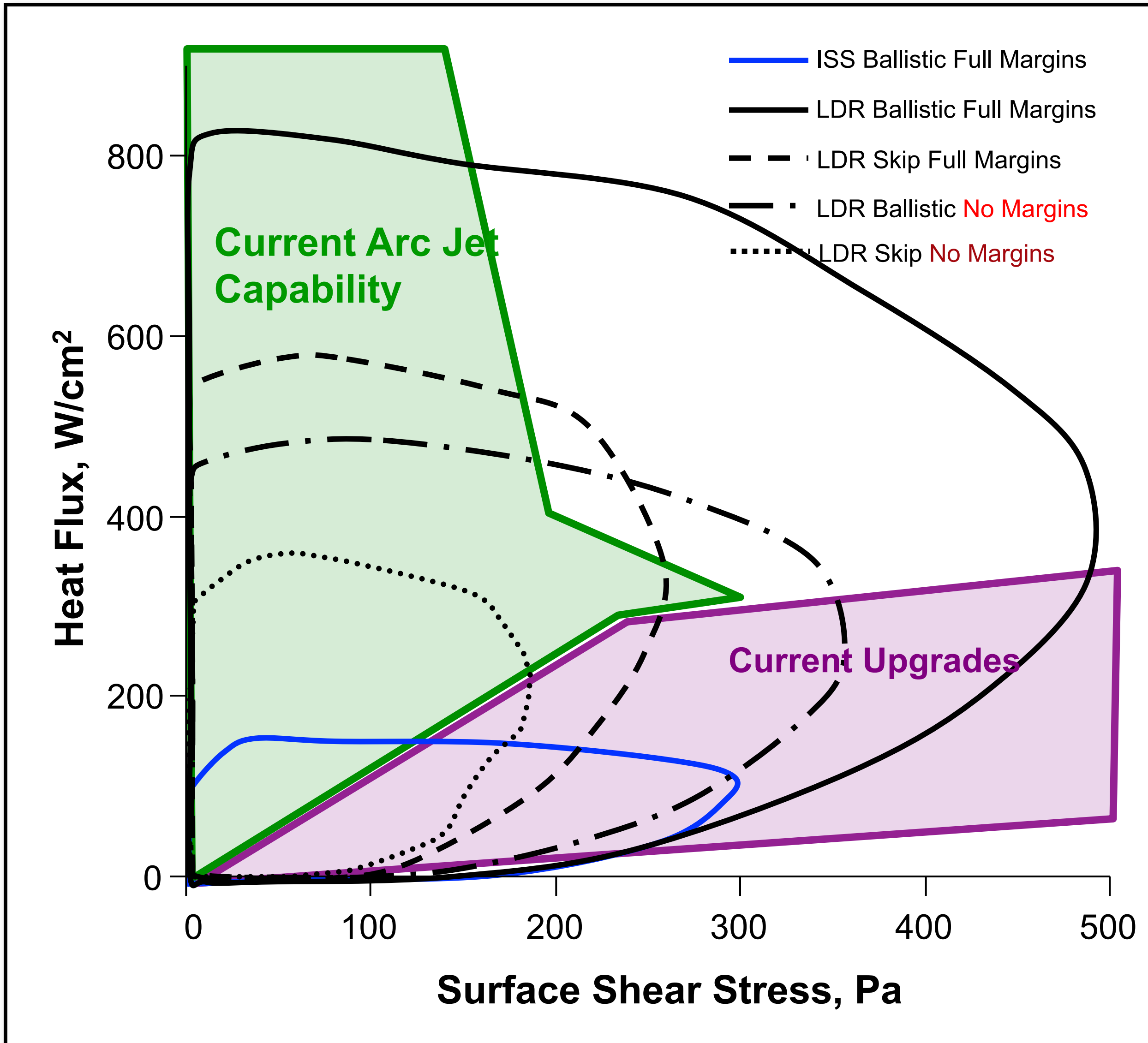




TPS Testing & IV&V : Arc Jet Capability

- **Arc jet Facility Test Capability**
  - Operational capabilities are limited
  - Test as you fly
  - Testing for failure
- **Challenges**
  - Thermal Performance and Material Capability Limit testing requires combined test environment relatable to flight
  - Laminar vs. Turbulent
  - Model Size and Nozzle Configuration
  - High vs. Low Enthalpy
  - Shear and Pressure Gradient

Current Test Capability in the US

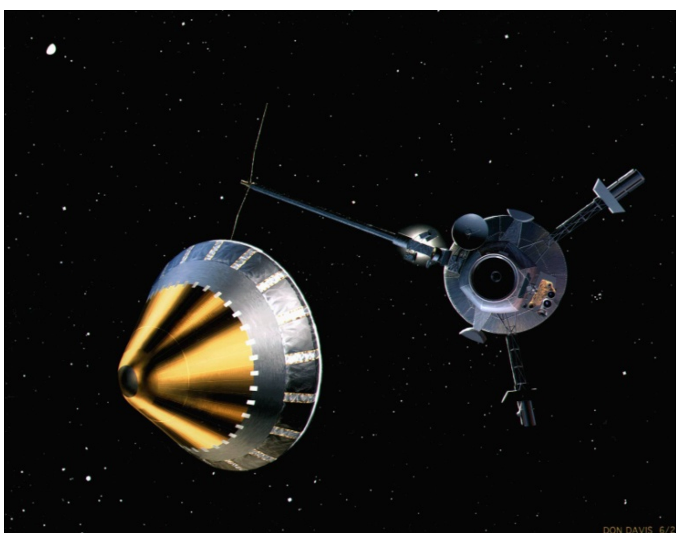


Stagnation Test Article
High Heat Flux/ Low Shear

Wedge Test Article
Moderate Heat Flux & Shear

Carbon Phenolic Story:

- **Galileo –**
  - still haven't deciphered flight data (recession sensors)
  - ground test a flight traceability issue
  - built GPF facility for Galileo but still couldn't simulate radiative heating
  - laser tests suggested char spall at worst conditions
- **Pioneer-Venus –**
  - material performed perfectly since environment not far removed from DOD applications
- **Saturn**
  - Is Carbon-Phenolic appropriate material?



Carbon Phenolic: Saturn Multi-Probe TPS

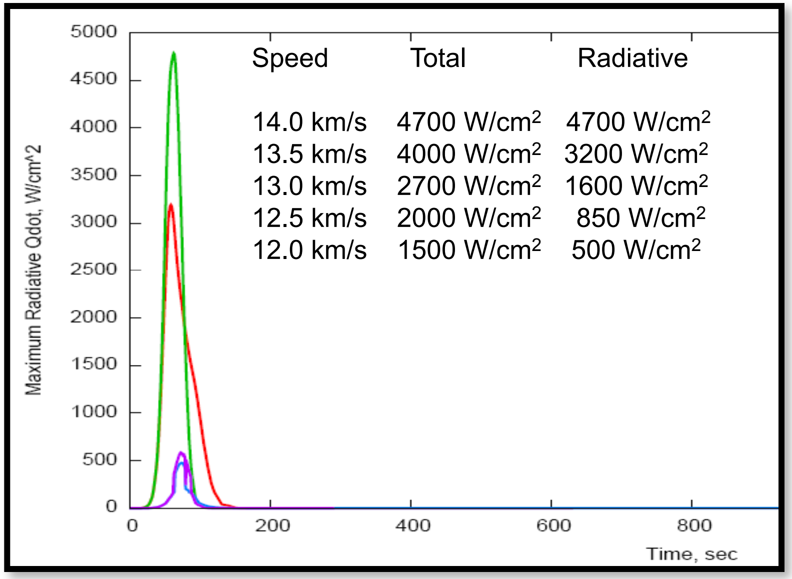
- TPS requirement at Saturn is less demanding than at Jupiter
- TPS mass-fractions for prograde entry is about 30% less than Galileo's
- Heating pulse about 2.5 times longer due to scale height difference. Therefore, Saturn probes have less ablation, but need more insulation
- Time to parachute deployment is about 5 minutes
- Carbon phenolic is well understood but it is not an optimum choice for this mission (large heat load would benefit from better insulator)
- Qualification testing for this mission is a challenge due to significant radiative heating component

Entry direct.	Latitude deg	Rel. entry V, km/s	Max diameter, m	Entry mass, kg	Max. heat rate, kW/cm^2	Max Heat Load kJ/cm^2	Forebody TPS mass fraction	Est. total TPS mass fraction	Max. decel., g
Pro.	6.5°	26.8	1.265	335	2.66	47.85	23.5%	25.8%	43.6
Pro.	45°	29.6	1,265	335	3.67	58.67	24.8%	27.3%	47.9
Retro.	6.5°	46.4	1,265	335	21.5	204.21	35.2%	38.7%	76.4

TPS Testing: Shock Layer Radiation

- **Lunar return, Mars return and Saturn radiation environment**
  - Lunar return ~(0.5 kW/cm2)
  - Mars Return ~(1 kW/cm^2 - 4 kW/cm^2)
  - Saturn ~(2 kW/cm^2 - 3 kW/cm^2)
- **During the Apollo era some arc jet facilities added carbon arc image or quartz lamps to simulate combined (radiative + convective) heating - that capability does not exist today**
  - No attempt was made to replicate the spectrum of radiative heating
  - Assumption was "radiation is radiation"
    - Probably OK for some materials (carbonaceous), but not all (glassy)
- **Combined heating ground test simulation is very important for some missions (high speed Earth return, Gas Giants, etc.)**
  - Need to be cognizant of radiative spectrum (atmospheric composition, velocity)
  - Requires definition of TPS spectral radiative properties
  - For many materials, interaction with radiative heating is very different than with convective heating
- **The TPS community needs to revisit this ground test simulation deficiency (or be willing to accept significant risk)**

Radiative Heating sensitivity with Earth Return Speed



Approach for Qual & Cert. of C-P:

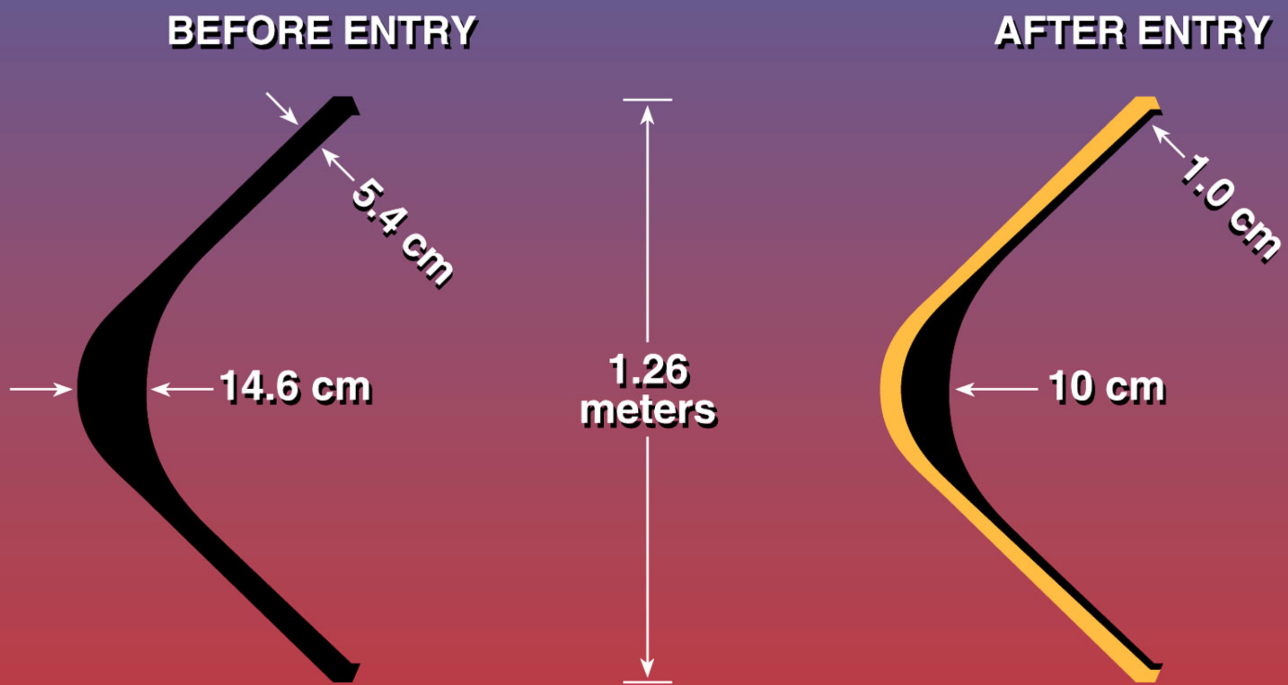
- Arc jet testing to evaluate performance to convective heating, pressure & shear
- Characterization of material optical properties in comparison to shock layer spectrum
- Use of high energy lasers to attain heat fluxes not achievable in arc jets

Concluding Remarks and Recommendations

- **Material performance forms the basis of any TPS selection. Requires capable / robust materials to start with**
  - Understanding limits and/or failure modes is important prior to baselining TPS materials to missions
    - Current modeling capabilities are limited. Testing is the only way to establish capability
  - System and Architecture issues are equally important and require development time for assessment
- **Heritage arguments often end-up being risky**
    - SLA for 5 m diameter HS that can handle 50 kJ/cm^2 heat load?
    - PICA for a 5 m diameter HS?
  - System, Architecture and Manufacturing issues need to be understood and solved
    - AVCOAT vs. PICA
  - When heritage material is no longer feasible, (precursors not available) the only option is replacement
    - Carbon Phenolic
- **Coordinated and Sustained Investment in TPS material and technology development to benefit wide range of missions.**
  - ISP and CEV TPS ADP
  - Planetary Exploration, both robotic and human missions, will require sustained investment in technology, people and facilities

End

Galileo Probe Heat Shield Ablation:
The Most Difficult Atmospheric Entry in the Solar System



152 kilograms

70 kilograms

Total initial mass of Probe:
335 kilograms

Ablated material

Ablation temperature = 3900° C